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STIMULUS-DEPENDENCY IN THE POWER-LAW SCALING OF THE SUBTHRESHOLD ACTIVITY OF V1 CELLS

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ABSTRACT

The power spectra of many nonlinear systems can display power-law frequency scaling with a fractional exponent. Such fractal behavior has been reported using various observables of neural activity from spike train statistics [4] to population dynamics [5]. However the origin of such scaling invariance remains controversial [6]. The analysis of the subthreshold membrane activity (Vm) in single neurons can help to dissect out the possible origins of the power-law. In the anesthetized and paralyzed cat, we recorded the intracellular response of V1 neurons to visual stimuli of various spatio-temporal statistics. We observed that, for each cell, the fractal exponent changes in a rather systematic way according to the stimulus. Such a dependency implies that local network dynamics are involved in the genesis of this power-law. We designed a model which derives the fractal exponent modulation from the topology of the functional connectivity. Using Cluster Point Process theory [2], we showed analytically that this effect depends on synchrony within local assemblies and that the emergence of power-law is further determined by the scaling property of network interactions. We led numerical simulations to confirm the power-law change at the Vm level. To check if those variations can be influenced by the cell intrinsic properties, this paradigm has been investigated in vitro using dynamic-clamp injections of generated conductances that reproduce fractal behaviour.

KEY WORDS

Fractal exponent, Synchrony, Membrane potential, Visual cortex, Dynamic clamp, Network correlations

1 Introduction

Among statistical measures, the power spectral density is a way to characterize correlations in the neural signals. This analysis can exhibit values of the powerlaw exponent (fractal exponent) which reflect self-similarities in the original signal. Fractal behavior has been reported using various observables of neural activity from spike train statistics [4] to population dynamics [5]. However the origin of such scaling invariance remains controversial [6].

2 Experimental results

The analysis of the subthreshold membrane activity (Vm) in single neurons can help to dissect out the possible origins of the power-law. In the anesthetized and paralyzed cat, we recorded the intracellular response of V1 neurons to visual stimuli of various spatio-temporal statistics. We observed that, for each cell, the fractal exponent changes in a rather systematic way according to the stimulus, for the same recorded neuron. Moreover, a multifractal analysis revealed that the membrane potential only displays monofractal behavior leaving the higher order terms negligible and stimulus-independent. Such a dependency on the fractal exponent implies that local network dynamics are involved in the genesis of this power-law.

3 Model

We designed a model which derives the fractal exponent modulation from the topology of the functional connectivity. Using Cluster Point Process theory [2], we showed analytically that this effect depends on synchrony within local assemblies and that the emergence of power-law is further determined by the scaling property of network interactions. We led numerical simulations to confirm the power-law change at the membrane potential and conductance level. We recovered the theoretical prediction for a reasonable amount of synchrony. The excitation/inhibition interplay is investigated and simple rules are found to describe the Vm fractal exponent according to the conductance decaying correlations.

Fractal behavior in neural network has been extensively studied in extracellular recording using Fano Factor measure. We show that those two quantities can be equivalent in some regimes. In this case, a linear relationship exists between the Fano Factor and Power Spectrum density fractal exponent.

4 Controls

Several controls have been done in order to invalidate other plausible explanations of this systematic exponent

change in in vivo experiments. We reproduced identical results for different input firing rate which could be elicited by the surrounding network and for different mean membrane potential. Those controls have been performed with conductance-based integrate-and-fire neurons as well as Hodgkin-Huxley neurons.

5 In vitro study

Using dynamic-clamp injections of excitatory and inhibitory conductances generated by our model with different fractal exponent values, our preliminary experiments conducted in vitro on rat cortical cells have revealed a strong dependence of the fractal behaviour of the recorded Vm against the power-law of the injected excitatory and inhibitory conductances. These results are consistent with our simulation predictions. Moreover, they suggest that intrinsic properties of the cells have little influence over the fractal behaviour of the recorded Vm.

6 Conclusion

Although the absolute value of the power spectrum slope, and thus of the fractal exponent, depends on the intrinsic properties of the recorded neuron, in the light of our results, we propose that the relative changes of the power law measured in vivo reflects changes in the correlation of the network activity surrounding the recorded cell.

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